(54) Title: X-RAY DIFFRACTION METHOD
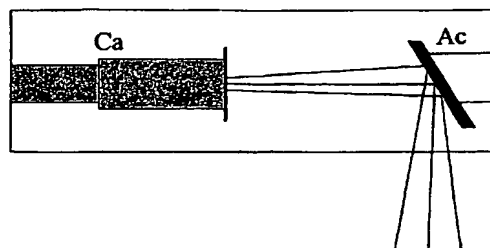
(57) Abstract: An X-ray diffraction method for the analysis of polycrystalline materials, the method comprising:(a) providing a polycrystalline material for analysis; (b) providing a polychromatic X-ray source, wherein the source produces X-rays by accelerating charged particles to energies of no more than 1 MeV; (c) collimating X-rays from the polychromatic X-ray source into a beam having a divergence in the range of from 10^{-4} to 10^{-2} radians;(d) exposing at least a portion of the polycrystalline material to the collimated X-ray beam, whereby the beam is diffracted;(e) collecting at least some of the diffracted X-rays in an energy dispersive X-ray detector or array; and(f) analysing the collected, diffracted X-rays.

X-ray Diffraction Method

The present invention relates to the field of X-ray diffraction of crystalline materials and, in particular, to an X-ray diffraction method for the determination of structural and/or chemical characteristics of polycrystalline engineering materials and components formed therefrom.

X-rays are electromagnetic radiation having a wave length of from 10^{-11} to 10^{-9} m and produced by bombardment of atoms by high-quantum-energy particles. In practice, X-rays may be produced by bombarding a metal target, for example copper or tungsten, with fast electrons in a vacuum tube.

The principle of X-ray generation in a vacuum tube is schematically illustrated in Figure 1. Electrons are emitted by the heated cathode (Ca) and accelerated by the applied voltage towards the anode (or anti-cathode, Ac) target. There they undergo rapid deceleration and absorption processes, which result in the emission of X-rays.

The radiation emitted as a result of the collision between electrons and the metal target can be separated into two components: (i) a continuous spectrum, which is spread over a wide range of wavelengths (also known as Bremsstrahlung); and (ii) a superimposed line spectrum, which is determined by the materials of the target (also known as the characteristic radiation).

The use of X-ray diffraction is of great importance in the analysis of crystals. For example, in the fields of metallurgy and materials science, X-

ray diffraction techniques may be used to identify the
lattice parameter and the structure of metal crystals.
Additionally, the techniques may be used to identify
the arrangement of different kinds of atoms in
5   crystals, the presence of imperfections, the
orientation of grains, the size of grains, the size
and density of precipitates and the state of lattice
distortion.

10   Known X-ray diffraction techniques include the
Laue method, the rotating crystal method and the
powder method (also known as the Debye/Scherrer
method).

15   In the Laue method a stationary single crystal is
bathed in a beam of polychromatic radiation. This
method is used for determining the orientation of
single crystals and the study of crystal
imperfections.
20

In the rotating crystal method a single crystal
is rotated in a beam of monochromatic X-rays. This
method is also used for the determination of crystal
structures.
25

In the powder method a powdered polycrystalline
sample is bathed in a beam of monochromatic radiation.
This method is used for the determination of lattice
parameters, grain sizes and the preferred orientation
30   of grains.

The powder method is also used to study bulk
polycrystalline samples, such as engineering
components and structures. For example, it can be
35   used to determine the lattice parameter variation in
orientation and position, and to deduce sample strain

and stress.

Conventional laboratory diffraction measurements
rely on interrogating only a thin ($\approx$ < 50 μm) surface
5   layer of the sample. Accordingly, such techniques do
not provide information regarding stresses and strains
in sub-surface regions or in the bulk of a sample.

Another widespread application of X-rays in
10   industry and medicine is radiography, i.e. for
transmission photography to obtain absorption
contrast-images. The only property of the X-ray
radiation that is utilised in such applications is the
penetrating ability.
15

In standard radiographic set-up, industrial
tungsten target X-ray tubes are used to produce
polychromatic radiation within a widely divergent
(~40°) cone.
20

In defectoscopic configuration, the object of
study, for example an aluminium casting, is bathed in
an incident X-ray beam, and a photographic plate or
CCD camera is used to record the image which registers
25   the attenuation of the beam along the path between the
source and any given pixel. This set-up is only
capable of providing information on relatively large
defects (typically about a millimetre in size), such
as casting voids.
30

For the purpose of quantitative diffraction
analysis, the radiation produced by an industrial X-
ray tube is not well suited in that it has a
definition that is too poor both in terms of wave
35   length (energy) and wave vector (direction).

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The present invention aims to address at least
some of the problems associated with the prior art.

In a first aspect the present invention provides
5   an X-ray diffraction method for the analysis of
polycrystalline materials, the method comprising:
(a)   providing a polycrystalline material for
       analysis;
(b)   providing a polychromatic X-ray source, wherein
10   the source produces X-rays by accelerating
       charged particles to energies of no more than 1
       MeV;
(c)   collimating X-rays from the polychromatic X-ray
       source into a beam having a divergence in the
15   range of from 10^{-4} to 10^{-2} radians;
(d)   exposing at least a portion of the
       polycrystalline material to the collimated X-ray
       beam, whereby the beam is diffracted;
(e)   collecting at least some of the diffracted X-
20   rays; and
(f)   analysing the collected, diffracted X-rays.

The following discussion applies to all aspects
of the present invention unless otherwise stated.
25

The source preferably produces X-rays by
accelerating charged particles to energies of no more
than 500 keV, more preferably to no more than 400 keV,
still more preferably to no more than 300 keV. The
30   source will typically comprise means to accelerate
electrons in a vacuum tube to impact a metal target.

The X-ray beam typically has a brilliance $\leq 10^{12}$
photons/s/mm²/mrad²/0.1% BW.
35

The diffracted X-rays may suitably be collected

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by an energy dispersive X-ray detector or array. For
example, a Li-drifted Si or Ge solid state detector
may be used. The energy dispersive X-ray detector
typically has a relative energy resolution of 0.5 x
10^{-2} to 4 x 10^{-2}, more typically 1 x 10^{-2} to 3 x 10^{-2}.
An example of a suitable detector is the Canberra BEGe
liquid nitrogen cooled, solid state energy dispersive
germanium crystal X-ray and gamma-ray detector, in
combination with multi-channel analyser, computer
acquisition software and hardware.

The energy of the collimated X-ray beam is
preferably $\geq$ 60 keV, more preferably in the range of
from 100 to 300 keV. This enables the collimated X-
ray beam to penetrate the polycrystalline material to
a depth of typically $\geq$ 1 mm, preferably $\geq$ 5 mm, more
preferably $\geq$ 10 mm, still more preferably $\geq$ 15 mm.
Indeed, the attenuation depth can be up to 50 mm or
more depending on the polycrystalline material. Thus,
sub-surface X-ray analysis may be achieved. The
attenuation depth is the thickness of material such
that the transmitted beam intensity is equal to 37% of
the incident beam intensity.

As mentioned above, the X-ray source will
typically comprise means to accelerate electrons in a
vacuum tube to impact a metal target. In this manner,
a metal target is bombarded with fast electrons. The
X-ray source is preferably an industrial X-ray source
(for example a tungsten target X-ray tube) such as may
be used in standard radiographic applications. A
suitable example is a 160 kV, 1.6 kW industrial X-ray
source (W tube) by Philips, supplied by AT Roffey Ltd
(circa 1980).

The beam may be collimated using known

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techniques. For example, a pair of adjustable copper-
tungsten X-ray slits may be used.

The method may further comprise moving the
collimated X-ray beam relative to the polycrystalline
material. In a preferred embodiment, the collimated
X-ray beam is scanned across at least a portion of the
polycrystalline material, while keeping the
polycrystalline material stationary. This is
advantageous in circumstances where the
polycrystalline material forms part of a relatively
large engineering component. In such cases, movement
of the component would be difficult.

The collected, diffracted X-rays may be analysed
in order to determine a structural and/or chemical
characteristic of the polycrystalline material, for
example lattice parameter determination. In turn,
lattice parameter determination may be used to provide
information on stresses and/or strains in the
polycrystalline material and, preferably, to map
stresses and/or strains. Stresses and/or strains in
the bulk of the polycrystalline material may be mapped
at a depth of typically $\geq$ 1 mm, preferably $\geq$ 5 mm,
more preferably $\geq$ 10 mm, still more preferably $\geq$ 15
mm. Indeed, stresses and/or strains in the bulk of
the polycrystalline material may be mapped at a depth
of up to 50 mm or more depending on the
polycrystalline material. This is in contrast to the
conventional laboratory techniques where only a thin
surface layer is analysed.

The polycrystalline material may be a natural
object or an engineering article or component part
thereof. The polycrystalline material will typically
comprise a metal or alloy, a ceramic or a crystalline

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polymer or a composite crystalline material, such as, for example, a ceramic reinforced metal matrix composite material. An example is SiC reinforced Al.

The polycrystalline material will typically have a thickness of ≥ 0.1 mm, more typically ≥ 1 mm, still more typically ≥ 5 mm, still more typically ≥ 10 mm, still more typically ≥ 15 mm. Indeed, the polycrystalline material may have a thickness of up to 50 mm or more depending on the absorption.

In contrast to the conventional powder diffraction techniques, the polycrystalline material need not be in the form of a fine grained powder, nor is material removal, cutting or drilling of any kind required within the region of interest. The method according to the present invention therefore allows engineering components to be analysed in their intended structural form. This is important for the measurement of sub-surface engineering stresses and strains.

In a second aspect, the present invention provides an apparatus for X-ray diffraction analysis of polycrystalline materials, the apparatus comprising:

(i)   a polychromatic X-ray source, wherein the source produces X-rays by accelerating charged particles to energies of no more than 1 MeV;

(ii)   means for collimating X-rays from the polychromatic X-ray source into a beam having a divergence in the range of from 10^{-4} to 10^{-2} radians;

(iii)   an energy dispersive X-ray detector or array for collecting at least some of the diffracted X-rays resulting, in use, from exposing at

least a portion of a polycrystalline material
to the collimated X-ray beam; and

(iv)   means for analysing the collected, diffracted
X-rays.

The polychromatic source may be moveable with
respect to a polycrystalline material to be analysed.
Advantageously, the collimated X-ray beam is adapted,
in use, to scan, across the sample of the
polycrystalline material, while the polycrystalline
material is maintained stationary.

In the method and apparatus according to the
present invention the polycrystalline material (for
example a component or sample) is preferably
maintained stationary, while an X-ray probe is moved
around it. The probe may comprise the X-ray source
and the detector, which may be fixed relative to each
other on a rigid arm.

In a third aspect, the present invention provides
a method of quantitatively mapping the sub-surface
distribution of the crystal lattice parameter in a
polycrystalline material, the method comprising:

(a)   providing a sample for analysis, wherein the
sample comprises a polycrystalline material;

(b)   providing a polychromatic X-ray source, wherein
the source produces X-rays by accelerating
charged particles to energies of no more than 1
MeV;

(c)   collimating X-rays from the polychromatic X-ray
source into a beam having a divergence in the
range of from 10^{-4} to 10^{-2} radians and an
attenuation length typically $\geq$ 1 mm;

(d)   scanning the collimated X-ray beam across the
sample, whereby the beam is diffracted;

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(e)   collecting at least some of the diffracted X-rays
       in an energy dispersive X-ray detector or array;
       and

(f)   analysing the collected, diffracted X-rays to map
5   the lattice parameter in the polycrystalline
       material.

The polycrystalline material may be a natural
material or, alternatively, an engineering material,
10   including a component formed therefrom.

This method may preferably be used to determine
the stresses and/or strains in polycrystalline natural
or engineering materials and components formed
15   therefrom. Accordingly, a preferred further step (f)
involves transforming the map of the lattice parameter
into a map of sub-surface engineering stresses and/or
strains.

20   The technique of composite strain mapping is
described in *Scripta Materialia*, Vol. 39, No. 12, pp.
1075-1712, 1988.

Typically, the present invention achieves a
25   strain measurement accuracy of 50×10^{-6} to 200×10^{-6},
more typically 100×10^{-6} to 150×10^{-6}. The spatial
resolution is typically from 0.25 mm to 1 mm.

Whole pattern fitting may be applied to extract
30   extremely accurate values of the lattice parameter
(better than 5×10^{-5}) and hence residual lattice
strain.

The present invention will now be described
35   further with reference to the following drawings, in
which:

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Figure 1 is a schematic illustration of the process of X-ray generation in a vacuum tube;

5   Figure 2 shows a diffraction configuration used in the Example (from right to left: incident beam - slits - sample - slits - detector);

Figure 3 shows the X-ray source spectrum (energy)
10   used in the Example;

Figure 4 shows the 'no sample' source pattern (lattice spacing) used in the Example;

15   Figure 5 shows a scattering pattern of a polycrystalline Al alloy sample used in the Example (log scale, counts);

Figure 6 shows a scattering pattern of a
20   polycrystalline Al alloy sample used in the Example (linear scale, counts);

Figure 7 shows a Gaussian fit to the Al diffraction peak 1 (the box on the right gives the
25   values and errors of the parameters);

Figure 8 shows a Gaussian fit to the Al diffraction peak 2 (the box on the right gives the values and errors of the parameters); and
30

Figure 9 shows an example of a multiple peak pattern that can be obtained from an aluminium alloy sample.

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Example

Transmission polychromatic X-ray diffraction
experiments were carried out on 1.5 mm thick samples
of rolled Al sheet. The strain accuracy achieved
(prior to optimization) was approximately 150×10^{-6}.
This corresponds to a stress accuracy of $\approx$ 10 MPa in
aluminium, $\approx$ 14 MPa in copper, and $\approx$ 28 MPa in steel.

The experimental set-up comprised:

a)   A 160 kV, 1.6 kW industrial X-ray source (W tube)
        by Philips, supplied by AT Roffey Ltd (circa
        1980), placed in a lead-lined room and position-
        controlled remotely using a traverse motor
        assembly;

b)   A Canberra BEGe liquid nitrogen cooled, solid
        state energy dispersive germanium crystal X-ray
        and gamma-ray detector, in combination with
        multi-channel analyser, computer acquisition
        software and hardware; and

c)   A pair of adjustable (0.5 to 5 mm) composite
        (copper tungsten) X-ray slits.

For the purpose of spatial definition the beam
was collimated using two large blocks of lead, about
50 mm thick, which only allowed radiation through a
long slit, 0.5 mm wide. This set-up was used in the
diffraction experiment. However, a secondary slit was
needed to further define the beam direction, and also
as an anti-scatter device. The two slits were aligned
using a laser pointer. Similarly, a pair of slits was
used on the detector side to provide directional
definition. In both cases the slits were mounted at

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two ends of a copper tube. Copper, a good photon absorber, was used to reduce secondary scatter.

While the incident beam was close to horizontal, the diffracted beam was defined to be inclined at an angle of about 6.2°.

A schematic illustration of the set-up is shown in Figure 2.

The lead block surfaces were irradiated by the intense incident X-ray beam and thus fluoresced (i.e. absorbed and re-emitted X-rays) at the characteristic wavelengths (energies) of Pb. This is evidenced by the energy spectrum shown in Figure 3. The characteristic energies present due to the 'source' properties do not change with the scattering angle prescribed by the set-up. However, the peaks of energy corresponding to diffraction from the crystal lattice of the sample depend on the scattering angle through Bragg's equation: $2d\sin\theta = n\lambda = hc/f$. This allowed the scattering angle to be adjusted so as to avoid, as far as possible, overlap with the 'signature' peaks of lead. Given a certain scattering angle θ, the energy pattern is converted to the lattice parameter pattern using Bragg's equation. For the configuration used, $\theta=3.1°$, and the 'no sample' pattern is shown in Figure 4.

The sample was then placed at the intersection of the incident and scattered beams. The sample contributed to the flux into the detector, through diffraction on many individual grains. New peaks appear in the pattern. This is illustrated in Figure 5, where a logarithmic scale is used for the vertical axis to make the peak at approximately 2.3Å more

prominent. Figure 6 shows the same profile using a
linear vertical scale for the counts.

Although the aluminium diffraction peak at
approximately 2.3Å in Figure 6 appeared broad and
small, fitting it with a simple Gaussian function
demonstrated that it provided acceptable accuracy.
The Gaussian peak shape used for this peak (dubbed
'Peak 1') was described by the function:

$$m2*exp(-(m0-m1)^2/2/m3^2)+m4 \qquad .$$

Here m0 is the argument (lattice spacing) and m1
to m4 are the function parameters that are sought.
The values of the parameters given above represent the
initial guesses. The result of fitting is shown in
Figure 7: Gaussian fit to the Al diffraction peak 1.
The box on the right gives the values and errors of
the parameters.

The fitting result corresponds to a strain
accuracy of $\Delta d/d=0.00033441/2.3304=145 \times 10^{-6}$. This
corresponds to a stress accuracy of about 10 MPa in
aluminium, 14.5 MPa in copper, and 29 MPa in steel.

The lattice spacing of 2.330 Å is close to the
value of $4.05/\sqrt{3}=2.338$ Å for the (111) reflection in
Al. The next reflection, (200), is expected at a
lattice spacing of 4.05/2=2.025 Å. Close inspection
of Figure 6 does indeed show that a peak exists at
approximately 2Å in that pattern, but is overlapped by
a characteristic twin of lead. However, provided this
twin is ignored in the analysis, this peak can be
fitted as well, as shown in Figure 8: Gaussian fit to
the Al diffraction peak 2. The box on the right gives
the values and errors of the parameters.

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The fitting result for peak 2 corresponds to a strain accuracy of $\Delta d/d = 0.0013964/2.0105 = 700 \times 10^{-6}$. This corresponds to a stress accuracy of about 50 MPa in aluminium, 70 MPa in copper, and 140 MPa in steel. The accuracy is affected by the overlap with the characteristic twin of Pb. Information from multiple peaks may be combined to improve the overall accuracy.

The lattice spacing of 2.01 Å is close to the value of 2.025 Å for the (200) reflection in Al. The ratio of the spacing for the two peaks is 1.15, which is very close to the theoretically expected value of 1.156 for the face centred cubic (fcc) lattice.

This Example demonstrates that the accuracy of lattice parameter determination is adequate for engineering stress measurement applications. The rate of data collection was approximately 15 minutes per pattern.

The method allows very efficient treatment of multiple peak diffraction patterns. An example of a multiple peak pattern that can be obtained from an aluminium alloy sample is shown in Figure 9. Whole pattern fitting can be applied to extract extremely accurate values of the lattice parameter (better than 5×10^{-5}) and hence residual lattice strain.

In the present invention, polychromatic beam/energy dispersive detector X-ray transmission experiments are used to analyse polycrystalline engineering materials and components.

The present invention provides a method of accurately determining the lattice parameter and thus stress measurements within the bulk of polycrystalline

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engineering materials and components. The present
invention enables quantitative measurements of
stresses (and preferred orientation) in components.
This may be achieved by accurate determination of
5   centre positions and intensities of multiple
diffraction peaks, not just their identification. The
entire (or substantially the entire) diffraction
pattern that has been collected may be analysed.

10   High energy X-rays are used to penetrate a
component or sample at very low angles (transmission).
Accurate beam collimation helps achieve the resolution
required for three-dimensional mapping of stresses.
During this procedure, the component or sample may be
15   maintained stationary, while an X-ray probe is moved
around it. The probe comprises the X-ray source and
detector fixed on a rigid arm thereby maintaining
their relative positions fixed.

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CLAIMS:

1.   An X-ray diffraction method for the analysis of
polycrystalline materials, the method comprising:
   (a)   providing a polycrystalline material for
         analysis;
   (b)   providing a polychromatic X-ray source, wherein
         the source produces X-rays by accelerating
         charged particles to energies of no more than 1
         MeV;
   (c)   collimating X-rays from the polychromatic X-ray
         source into a beam having a divergence in the
         range of from 10^{-4} to 10^{-2} radians;
   (d)   exposing at least a portion of the
         polycrystalline material to the collimated X-ray
         beam, whereby the beam is diffracted;
   (e)   collecting at least some of the diffracted X-
         rays in an energy dispersive X-ray detector or
         array; and
   (f)   analysing the collected, diffracted X-rays.

2.   A method as claimed in claim 1, wherein the
source produces X-rays by accelerating charged
particles to energies of no more than 500 keV.

3.   A method as claimed in claim 1 or claim 2,
wherein the energy dispersive X-ray detector has a
relative energy resolution of from 0.5×10^{-2} to 5×10^{-2}.

4.   A method as claimed in any one of the preceding
claims, wherein the energy of the collimated X-ray
beam is. $\geq$ 60 keV, preferably in the range of from 100
to 300 keV.

5.   A method as claimed in any one of the preceding

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claims, wherein the collimated X-ray beam penetrates the polycrystalline material to an attenuation depth of ≥ 1 mm.

6. A method as claimed in any one of the preceding claims, further comprising moving the collimated X-ray beam relative to the polycrystalline material.

7. A method as claimed in claim 6, comprising scanning the collimated X-ray beam across at least a portion of the polycrystalline material, while keeping the polycrystalline material stationary.

8. A method as claimed in any one of the preceding claims, wherein the collected, diffracted X-rays are analysed in order to determine a structural and/or chemical characteristic of the polycrystalline material.

9. A method as claimed in claim 8, wherein the structural characteristic is the lattice parameter.

10. A method as claimed in claim 9, wherein lattice parameter determination is used to provide information on phase distributions, stresses and/or strains in the polycrystalline material.

11. A method as claimed in claim 10, wherein lattice parameter determination is used to map phase distributions, stresses and/or strains in the polycrystalline material.

12. A method as claimed in claim 11, wherein lattice parameter determination is used to map phase distributions, stresses and/or strains in the polycrystalline material at a depth of ≥ 1 mm.

13.   A method as claimed in any one of the preceding claims, wherein the polycrystalline material is an engineering article or component part thereof.

5   14.   A method as claimed in any one of the preceding claims, wherein the polycrystalline material comprises a metal or alloy, ceramic or crystalline polymer, including combinations of two or more thereof.

10   15.   A method as claimed in any one of the preceding claims, wherein the polycrystalline material is a composite material comprising a crystalline phase.

16.   A method as claimed in claim 15, wherein the
15   metal matrix composite material is a glass and/or ceramic reinforced metal matrix composite material.

17.   A method as claimed in any one of the preceding claims, wherein said portion of the polycrystalline
20   material has a thickness of ≥ 1 mm.

18.   An apparatus for X-ray diffraction analysis of polycrystalline materials, the apparatus comprising:
       (i)   a polychromatic X-ray source, wherein the
25   source produces X-rays by accelerating charged particles to energies of no more than 1 MeV;
       (ii)   means for collimating X-rays from the polychromatic X-ray source into a beam having a divergence in the range of from 10^{-4} to 10^{-2}
30   radians;
       (iii)   an energy dispersive X-ray detector or array for collecting at least some of the diffracted X-rays resulting, in use, from exposing at least a portion of a polycrystalline material
35   to the collimated X-ray beam; and
       (iv)   means for analysing the collected, diffracted

X-rays.

19.   An apparatus as claimed in claim 18, wherein the
polychromatic source is moveable with respect to a
polycrystalline material to be analysed.

20.   An apparatus as claimed in claim 18 or claim 19,
wherein the collimated X-ray beam is adapted, in use,
to scan, across the polycrystalline material, while
the polycrystalline material is maintained stationary.

21.   A method of quantitatively mapping the sub-
surface distribution of the crystal lattice parameter
in a polycrystalline material, the method comprising:
(a)   providing a sample for analysis, wherein the
      sample comprises a polycrystalline material;
(b)   providing a polychromatic X-ray source, wherein
      the source produces X-rays by accelerating
      charged particles to energies of no more than 1
      MeV;
(c)   collimating X-rays from the polychromatic X-ray
      source into a beam having a divergence in the
      range of from 10^{-4} to 10^{-2} radians, and a
      penetration depth of $\geq$ 1 mm;
(d)   scanning the collimated X-ray beam across the
      sample, whereby the beam is diffracted;
(e)   collecting at least some of the diffracted X-
      rays in an energy dispersive X-ray detector or
      array; and
(f)   analysing the collected, diffracted X-rays to
      map the lattice parameter in the polycrystalline
      material.

22.   A method as claimed in claim 21, wherein the
polycrystalline material is a natural material or an
engineering material, including a component formed

therefrom.

23.   A method as claimed in claim 21 or claim 22,
further including:
(f)   transforming the map of the lattice parameter
       into a map of sub-surface engineering stresses
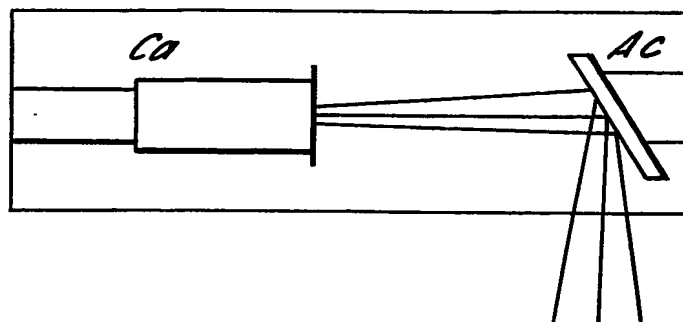   and/or strains.

FIG. 1.

FIG. 2.
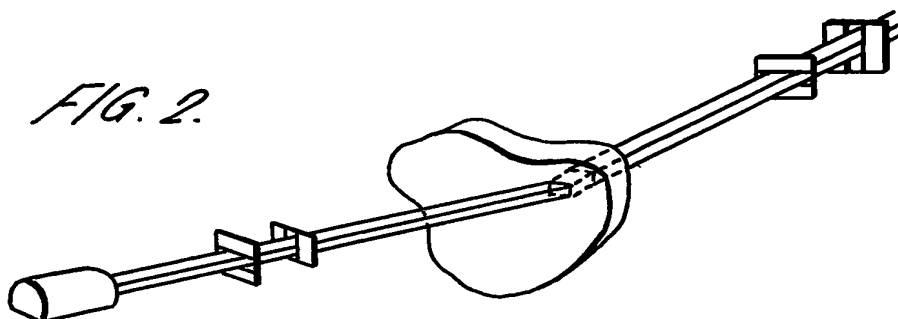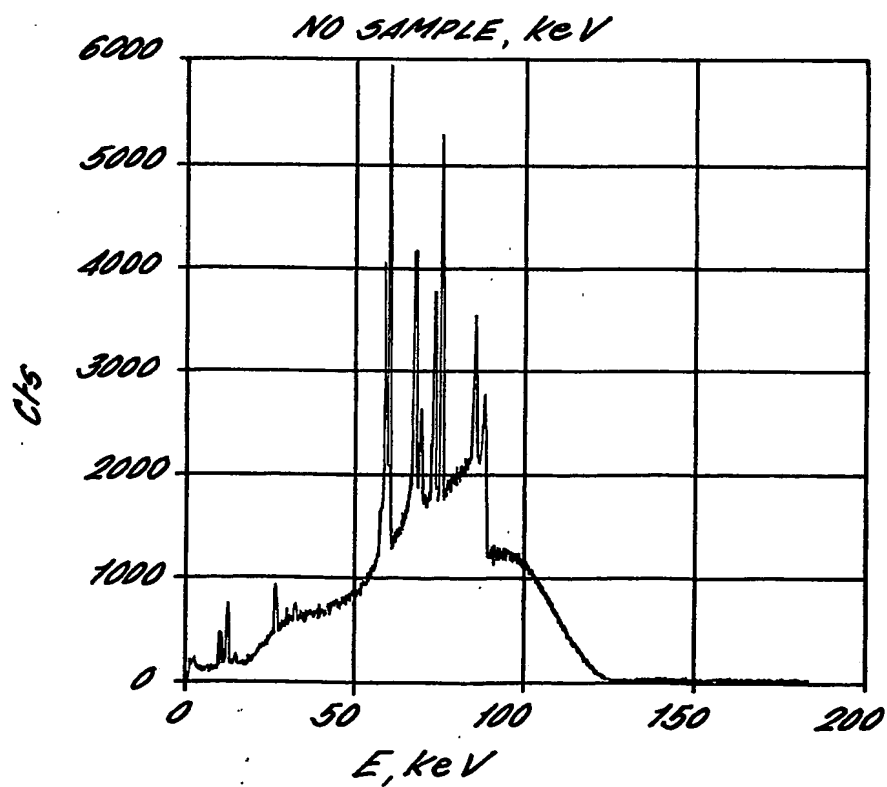

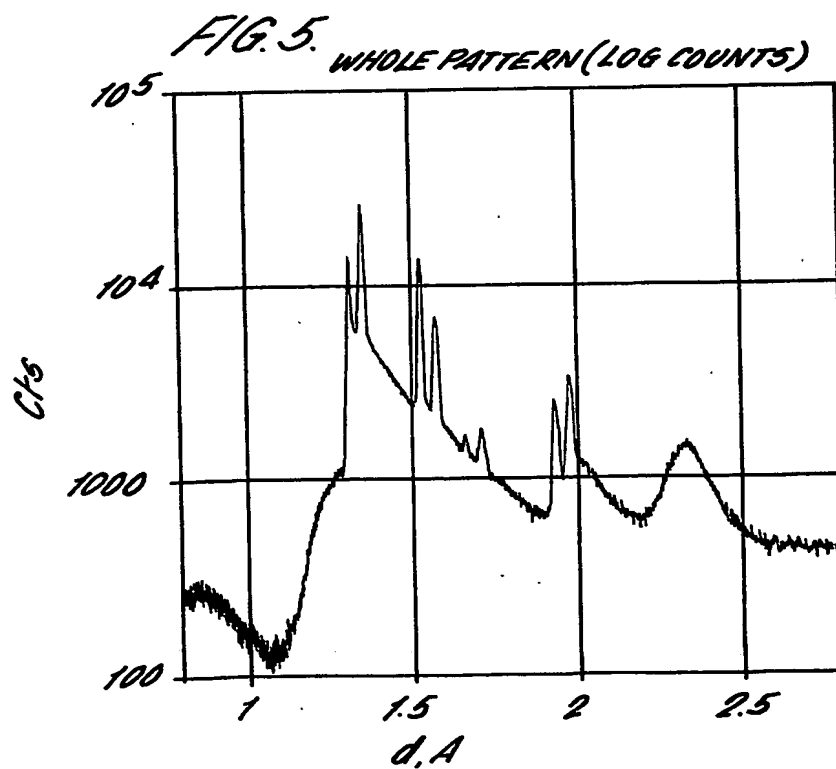FIG. 3.

NO SAMPLE, KeV

E, KeV

FIG. 4.

NO SAMPLE

FIG. 5. WHOLE PATTERN (LOG COUNTS)

FIG. 6.

WHOLE PATTERN (LIN COUNTS)

FIG. 7.

PEAK 1
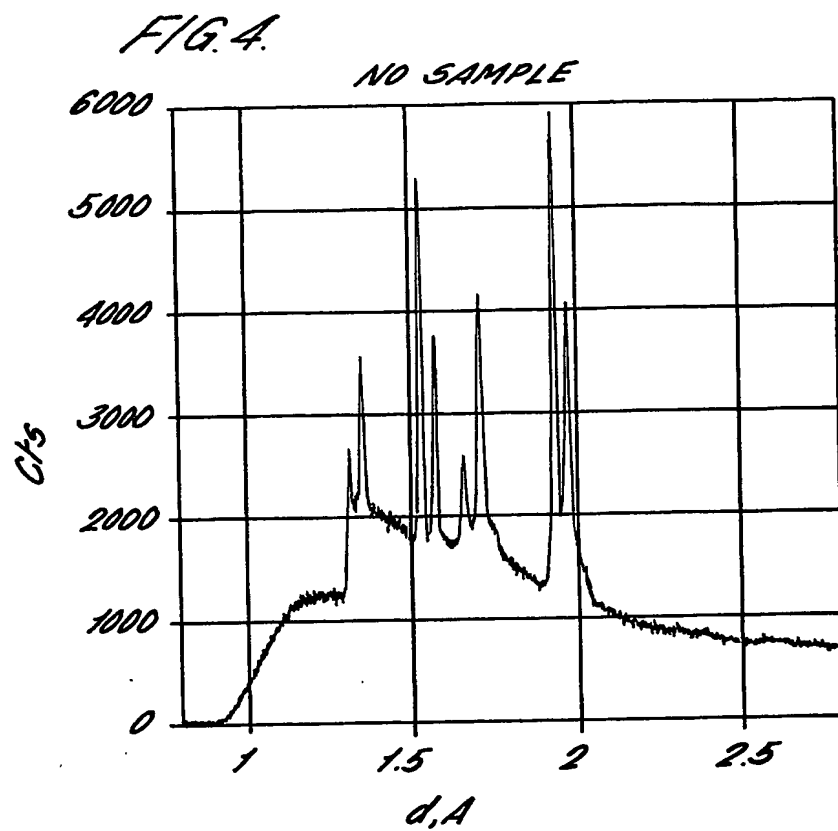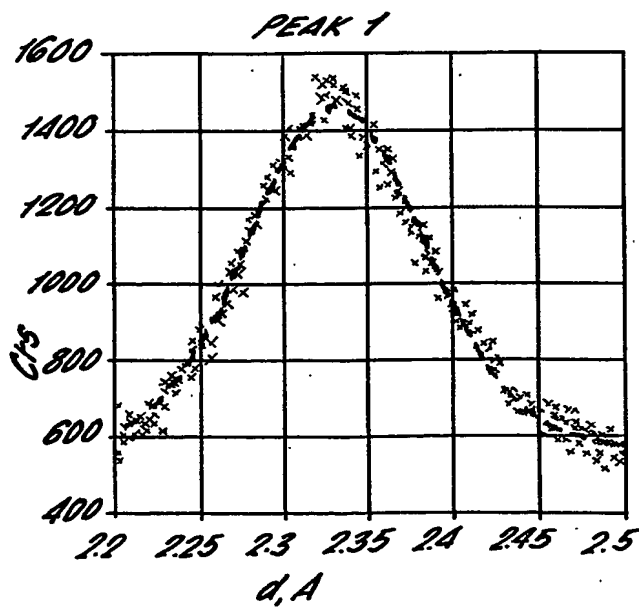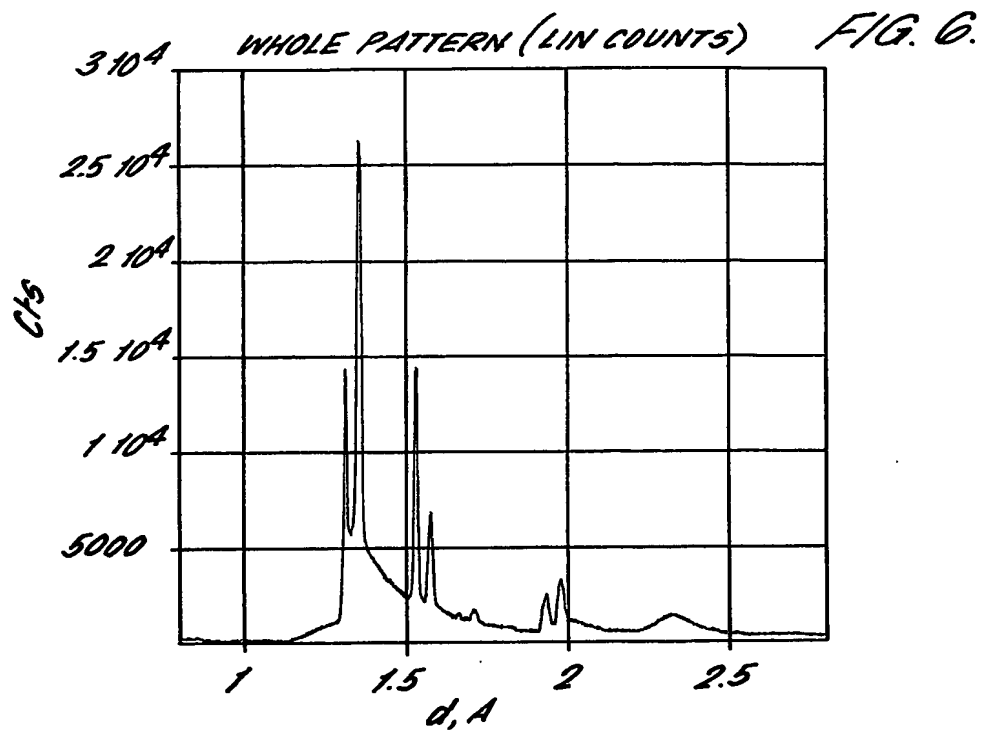
y=m2*exp(-(m0-m1)^2/2/m3^...		
	Value	Error
m1	2.3304	0.00033441
m2	886.11	6.7817
m3	0.052465	0.00057504
m4	572.99	6.1367
Chisq	3.8277e+05	NA
R	0.99281	NA

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FIG. 8.

PEAK 2
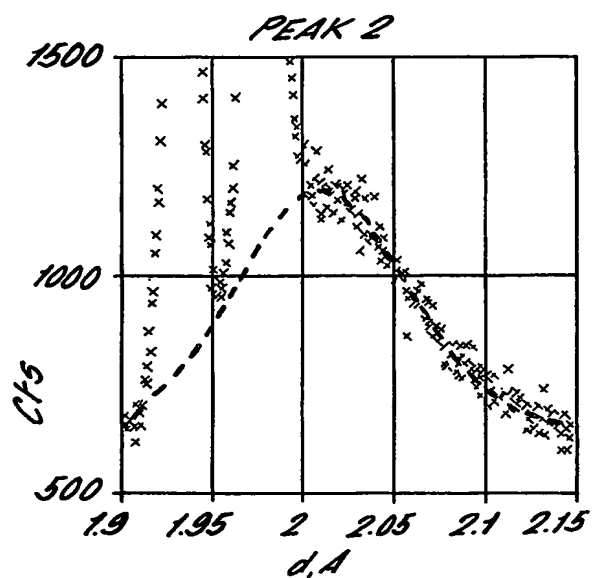
$y=m2*exp(-(m0-m1)^2/2/m3^...$		
	Value	Error
m1	2.0105	0.0013964
m2	546.57	9.2459
m3	0.046939	0.0015414
m4	650.02	7.4931
Chisq	2.0525 e+05	NA
R	0.98723	NA

FIG.9.